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SOLID FILM LUBRICATION RESEARCH

D. J. Boes
E. S. Bober

Quarterly Progress Report No. 6
1 March 1967 - 1 June 1967

Contract No. AF 33 (615)-2618
Project 3145 - Task 314502

Westinghouse Electric Corporation
Research Laboratories
Pittsburgh, Pennsylvania 15235

For

Air Force Aero Propulsion Laboratory
Research and Technology Division
ATTN: APFL
Wright-Patterson Air Force Base, Ohio 45433

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FOREWORD

This report was prepared by the Westinghouse Electric Corporation, Westinghouse Research Laboratories, Insulation & Chemical Technology Department, Beulah Road, Churchill Borough, Pittsburgh, Pennsylvania 15235, under USAF Contract No. AF 33 (615)-2618. The contract was initiated under Project 3145, "Dynamic Energy Conversion Technology," Task 314502, "Solar Dynamic Power Units." The contract is being continued under Project 8128, "Power Conversion Conditioning and Transmission Technology," Task 812802, "Mechanical Power Transmission and Control and Project 3044, "Aerospace Lubrication," Task 304402, "Advanced Propulsion Lubrication Engineering." The work is being administered under the direction of the Air Force Aero Propulsion Laboratory, Research and Technology Division, with Mr. J. S. Cunningham acting as project engineer. Accordingly, questions relative to this work may be directed to:

Air Force Aero Propulsion Laboratory
ATTN: APFL (Mr. J. S. Cunningham)
Wright-Patterson Air Force Base, Ohio 45433

This report covers work conducted from 1 March 1967 to 1 June 1967.

Approved for:
Westinghouse Electric Corporation

Daniel Berg

Daniel Berg, Manager
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ABSTRACT

This report describes progress during the eighth quarterly period in a program designed to develop a solid film lubricated ball bearing system capable of operation under high speed, high temperature oxidizing conditions. The program's ultimate goal is long-term ball bearing operation at 1500°F and speeds of 10,000 to 30,000 rpm under atmospheric conditions simulating sea-level to 200,000 ft altitudes. A second program objective is to provide parametric design data relating the operating life, load, bearing size, speed, temperature and environment of these bearing systems.

In the materials development area, this report describes further efforts towards improving the high temperature friction-wear characteristics of unique self-lubricating composites employing WSe_2 or WS_2 in combination with a gallium alloy.

In the area of functional testing, the results of thirty-three tests on 204 and 207 ball bearings that were evaluated during this reporting period are described. The bearings were operated at temperatures up to 900°F and speeds of 10,600 rpm. Two significant results obtained during this reporting period are the operation of (1) a 207 ball bearing in 600°F-air at 10,600 rpm for a period of 105 hours, and (2) an identical bearing system at 10,600 rpm in a 900°F environment for a period of 38 hours. In both cases the bearing carried a 50 lb thrust/50 lb radial load.

I. INTRODUCTION

Proper lubrication is a prime requisite for the successful operation of any load-bearing surface that undergoes a relative motion between itself and a second component of a system. But, when the load-bearing surface is exposed to a high-temperature oxidizing environment, the lubrication problem is greatly complicated by the effect of environment on the lubricant. Two major effects result from such an environment: First, there is a loss of conventional lubricants through evaporation and chemical decomposition. Secondly, through an oxidation process, solid lubricants are transformed to relatively abrasive metal oxides. The resulting substantial increase in friction eventually brings about the catastrophic failure of the load-bearing system by means of a wear mechanism.

This program is designed to develop solid film lubrication systems capable of long term operation in atmospheres characteristic of those from sea level to 200,000 ft, at temperatures from -45 to +1500°F, and at speeds approaching 30,000 rpm. The program has two major objectives:

1. To optimize the physical properties of certain unique, self-lubricating composites and thereby provide materials that are both physically and chemically capable of functioning as self-lubricating load-bearing surfaces in an extreme-temperature oxidizing environment.

2. To functionally evaluate the performance of high-speed ball bearings utilizing these composites as self-lubricating retainers. Parametric design data relating the operating life, load, bearing size, speed, temperature, and atmospheric environments is being obtained.

The materials optimization portion of the overall effort has emphasized the evaluation of candidate materials with respect to friction coefficients, wear resistance, mechanical strength and oxidation resistance. The effect of elevated temperature, oxidizing environments on the friction-wear characteristics of candidate composites under high sliding velocities is also being determined.

The functional test portion of the program, in a step-wise approach, is designed to demonstrate long-term operation at successively higher temperatures of 600, 900, 1200, and 1500°F.

II. EXPERIMENTAL

A. Materials Support Program

1. Metal Fillers

As reported in Quarterly Progress Report #5,(1) it had been discovered that the incorporation of a 20% (wt) concentration of Cu and W powders (1:1 ratio) as a metal filler in the WS_2/GaIn composite resulted in an increase in compressive strength from 15000 psi to 26000 psi. Furthermore, use of the same filler in an identical concentration and ratio in the WSe_2/GaIn composite increased its average compressive strength from 20000 psi to 47000 psi. During this reporting period the effect on composite strength of metal-filler combinations other than Cu-W was determined in a study that included the use of the fillers in concentrations of both 10 and 20% (wt). All specimens were fabricated at room temperature and pressures of 50,000 psi. Fillers included in the study were Cu with Ta, Mo, and Ag and Ni with W, Ta, Mo and Ag. The filler blend ratio was 1:1 in all cases. The results of compressive strength tests run on these specimens is given in Table I. It will be noted that a slight improvement in strength was achieved over the basic WS_2/GaIn composite in all cases involving a copper-metal filler. None of the materials, however, matched the compressive strength of the Cu-W filled WS_2/GaIn composite (25,900 psi) described previously. It is also seen from these data that the substitution of nickel for copper in these various filler blends resulted in severe pellet cracking and delamination during the final 1000°F cycle of their cure. Based on these data, it was decided to concentrate any further studies of blended filler composites to the Cu-W system.

In Table II the results of experiments investigating the use of lower concentrations of Cu and Cu-W fillers in both WSe_2/GaIn and WS_2/GaIn composites are given. The need for these tests will be detailed in the Functional Test Section of this progress summary. For each composite composition pellets were fabricated where possible at four different pressures. All specimens were prepared at room temperature and contained 90% (wt) of the basic lubricant-gallium/indium aggregate.

In the case of Cu and Cu-W filled WS_2/GaIn composites, it was found that compressive strengths could be held at the 18000 to 20000 psi level with the use of only 10% (wt) filler. In this concentration, however, no advantage was found in the use of a Cu-W blend rather than copper only. A marked decrease in strength was observed when 5% (wt) less gallium/indium was used in the WS_2/GaIn aggregate. Upon substitution of WSe_2 for WS_2 in the same series of experiments, it was found that the Cu-W filler provided stronger composites than those utilizing Cu only, particularly when the specimens were fabricated at 50,000 psi or less. In view of these encouraging results with regard to composite strength, the various formulations were further evaluated on the Hohman friction-wear apparatus over a 900°F temperature range. The results of these tests are summarized in Table III. It will be noted that all compositions provided good to excellent wear resistance from room temperature to 900°F under high surface speed conditions. The wear results at 900°F are misleading, however, unless evaluated in conjunction with the friction coefficient and the type of film deposits on the shaft surface. It will be noted that at 900°F friction coefficients increase sharply as filler content exceeds 10% (wt). This is not the case at 600°F, where oxidation of the film is far less severe. In general, poorer filming ability was exhibited by those compositions containing 20% (wt) or more filler. Finally, in all cases the WS_2 based compositions demonstrated slightly better wear resistance and filming ability than their WSe_2 counterpart. The effect of these higher friction coefficients and lower filming tendencies on 900°F bearing operation will be discussed in more detail in the Functional Test Section of this report.

2. WSe_2 Synthesis and WSe_2/GaIn Aggregate Preparation

During this reporting period a program designed to study the effect of synthesis temperature, ball-milling time, and curing cycle on the physical and lubricating characteristics of the WSe_2/GaIn composite was completed. Tungsten diselenide, synthesized at both 930 and 1380°F maximum temperature were combined with the gallium-indium eutectic by ball-milling for periods ranging from 15 minutes to 90 minutes. The

aggregate was then fabricated at various pressures into 1/2" diameter pellets and evaluated with regard to compressive strength. The results of these experiments are tabulated in Table IV. It was found that reducing ball-milling time from 60 minutes to 15 or 30 minutes causes the compressive strength of the composite to be far more sensitive to fabricating pressure regardless of the temperature at which the tungsten diselenide is synthesized. For composites fabricated from material ball-milled 30 minutes or less, adequate mechanical strength can be achieved only by fabrication at 100,000 psi. From the data it is also clear that a 60 and a 90 minute minimum ball-milling period is required for the 1380°F and the 930°F material respectively before this observed dependence on fabricating pressure is eliminated. Based on these data, it seems apparent that there is no basis for modifying either the technique used in synthesizing WSe_2 or the ball-milling procedure used in preparing the WSe_2/GaIn aggregate. It is also apparent that changing one or both of these parameters can greatly alter composite properties. These procedures will therefore remain unchanged and are as follows:

WSe_2 Synthesis	- 15 hour anneal at 1380°F
WSe_2/GaIn Preparation -	
Ball Milling	- 60 minutes minimum
Speed	- 75 rpm
Charge	- 600 gms
Volume	- 1 quart mill - 50 rollers 3/4" diameter x 1"

In conjunction with the above experiments, it was also decided to evaluate the various preparations with regard to their high speed wear resistance at 900°F. The experiments were conducted on the Hohman tester at 2550 fpm and a 3 lb line contact on a 1/4" face. Similar experiments had previously shown that the WSe_2/GaIn composite suffered a sharp increase in wear rate (scar = 16 mm) at the 900°F temperature level (See Test #1, Table V). It was quite surprising, therefore, to discover that WSe_2/GaIn specimens made from material employing WSe_2 synthesized at 930°F apparently exhibited an excellent wear resistance (scar = 3-1/2 mm) at 900°F. The result was reproducible and held true

for both 15 and 30 minute ball-milled material. In addition, specimens made from standard WSe_2 (1380°F synthesis) but ball-milled only 15 minutes also demonstrated excellent 900°F wear resistance. In both cases the specimens had been given a maximum cure of 1030°F. In view of these results, a set of 204 rings were fabricated employing 930°F WSe_2. After exposing the rings to a cure identical to that given the previous specimens, they were cut into Hohman blocks and their wear characteristics measured at 900°F. The results of these tests are listed in Table V as tests #5 through #7. It is apparent that these results correspond to the high wear rates observed prior to this investigation, giving wear scars > 15 mm. In addition, specimens cut from a 207 size ring using standard WSe_2 also exhibited the 900°F high wear characteristic.

To establish if either WSe_2 synthesis temperature or WSe_2/GaIn curing temperature were responsible for providing the improved wear rates observed in earlier tests, four specimens were prepared in which ball-milling time was held constant at 90 minutes while synthesis temperature and curing cycle were varied. All specimens gave excellent wear rates at 900°F.

Based on these first 13 tests, it appeared that none of the parameters thus far investigated, including ball-mill time, curing cycle, or synthesis temperature, could explain the excellent wear observed in some samples and the poor wear observed in others. It was noted, however, that high wear was always obtained in samples cut from large rings while low wear was consistently measured on specimens fabricated as blocks suitable for immediate screening on the Hohman test. Test #7 had apparently eliminated the possibility that a surface coating, formed on the blocks during the curing cycle, caused low wear; a coating which was naturally lost by cutting the specimens from rings. It was therefore decided to determine if fabricating pressure - the only remaining variable - was responsible for the widely varying wear rates. It had been established that all blocks had been fabricated at a pressure of 25,000 psi while the 204 and 207 size rings had been made under a pressure of 43,000 psi. A series of five blocks were therefore fabricated

over a pressure range of 14,500 to 60,000 psi. The specimens were made from the same batch of material and cured simultaneously to 1030°F. High speed wear measurements on these pellets, given in Table VI, revealed that those samples fabricated at 35,000 psi or higher exhibited high wear characteristics. A series of 204 rings were therefore prepared at pressures ranging from 11,500 psi to 23,000 psi with the expectation that specimens cut from any of these rings should exhibit low wear characteristics. As shown in Table VI, tests #23 through #26, high wear characteristics were obtained from all rings.

As a final effort to resolve the problem, 1/16" was removed from the face of two blocks that had given low wear at 900°F and the samples re-run. In both cases, a high wear characteristic was obtained. These last two tests, therefore, confirm that the low wear characteristic observed in specimens made as a block is indeed caused by a surface coating formed on the sample during the curing cycle. The depth of penetration of this coating, however, is a function of the pressure at which the sample is fabricated. Thus, for specimens made at 25,000 psi or less, the porosity of the piece is such that the coating can penetrate into the body to a depth sufficient to provide low wear at 900°F. Reproducibility was obtained because the block was simply reversed for the second test. Block specimens fabricated at pressures greater than 25,000 psi are less porous, causing thinner surface coatings and progressively higher wear rates. Naturally, specimens cut from rings, regardless of the pressure at which they were made, will always exhibit high wear due to the absence of the surface coat. Test #7, made on the outer surface of a ring, which contained this coating, did not exhibit low wear because the ring had been fabricated at 43,000 psi, giving a relatively non-porous body.

In Table VII it is interesting to note that the lack of a surface coating does not deleteriously affect the wear characteristic of either the WS_2/GaIn composite or metal-filled composites. This suggests that the basic WSe_2/GaIn composite is perhaps filming metal surfaces too heavily. At 900°F, the oxidation of this film presents a relatively abrasive surface to the block (or retainer) face causing a sharp increase

in wear rate. Recent experiments have indicated that the addition of fillers, such as Cu, Ag, and CaF_2, in concentrations of 2 to 5% (wt), do in fact improve the high temperature wear resistance of the WSe_2/GaIn composite. The following table illustrates this effect.

WEAR RESISTANCE AT 900°F OF FILLED WSe_2/GaIn COMPOSITES
2550 fpm - 3 lb load on 1/4" face

Composition Wt %	Friction Coefficient	Scar Dia. - mm
97-1/2% WSe_2/GaIn - 2-1/2% Cu	0.14	4
95% WSe_2/GaIn - 5% Ag	0.25	9-1/2
47-1/2% WSe_2/GaIn - 47-1/2% WS_2/GaIn - 5% Cu	0.14	4
99% WSe_2/GaIn - 1% CaF_2	0.11	4
98% WSe_2/GaIn - 2% CaF_2	0.25	6-1/2

As will be seen from the results of functional tests on these materials, however, additional development is required before optimum combinations are achieved.

B. Functional Test Program

1. High Temperature Bearings

Figures 1 and 2 present the designs of the 204 size bearings being fabricated for the 1500°F functional test work. Bearing rings and balls are of K-162 B Kentanium. Bearings of the first design (Figure 1) are similar to those currently on test in the 600 and 900°F programs, although radial clearances have been increased and the bearing width changed from 0.550 to 0.984". The second design, Figure 2, employs an angular contact ball bearing with the inner race relieved. Lubricant recesses have been included in this design to permit installation of lubricant "rails" in the outer ring. It is planned to use this design primarily for 21000 rpm testing.

2. High Speed Films of Retainer Action at 21,500 rpm

In an attempt to establish if cage density (and, as a result, unbalance) or ball density is responsible for the cage instability

observed at speeds of 21,500 rpm, a series of high speed films were obtained of the following systems:

(a) Graphite Retainer - 8 M2 balls

(b) Graphite Retainer - 8 TiC balls

(c) WSe_2/GaIn Retainer - 8 TiC balls

The film was taken at 4000 frames/sec while the bearings were operating at room temperature and a load of 50 lbs thrust/50 lbs radial. The film has been forwarded to the Aero Propulsion Laboratory, WPAFB, for evaluation.

3. High Temperature Test Facilities

The fabrication of the necessary components for construction of two high temperature test spindles has been completed. The parts, which include shafts, test bearing housing, loading devices, and associated hardware, were machined from Rene 41. Assembly of these test stands will be completed during the next reporting period. In addition, the fabrication of inserts and adapters required for functional testing of 206 - Stellite bearings at 1200°F has been completed. Twenty-four of these bearings are available for test purposes.

4. Functional Test Results

A total of thirty-three tests on 204 and 207 size ball bearings were performed during this reporting period. The results of these tests are summarized in Tables VIII and IX. With regard to the 204 system, all tests were operated at a speed of 10,600 rpm and, with the exception of a room temperature life test, at a temperature of 900°F. The primary purpose of 204 testing in this period was to evaluate their 900°F performance when equipped with self-lubricating retainers employing various metal fillers. These fillers were employed in an attempt to improve both wear resistance and mechanical strength. In general, the 900°F life and operating characteristic of metal-filled retainers were found to be poorer than those of retainers fabricated from the basic solid lubricant-gallium/indium composites. It is emphasized here that this deterioration of performance observed with the use of filled retainers

at $900^{\circ}F$ may not apply for the -40 to $600^{\circ}F$ temperature range. Supporting evidence for this belief is Run #191, which provided a life of 362 hours on a metal-filled retainer system at room temperature. This is a 60 hour improvement over the life obtained with the basic WSe_2/GaIn retainer under identical operating conditions. In addition, Hohman data (Table III) on these materials shows that little if any increase in friction or wear is observed in moving from room temperature to $600^{\circ}F$. Only upon reaching $900^{\circ}F$ does the material suffer a sharp increase in friction coefficient.

It is the authors' belief that the reason behind the reduction in life observed with metal-filled composites lies in the f. :t that $900^{\circ}F$ is well beyond the threshold oxidation temperature of the solid lubricants currently being employed. Solid lubricant films being transferred to the bearing surfaces are therefore required to handle a far more difficult lubrication job at $900^{\circ}F$ than at $600^{\circ}F$, particularly under the operating conditions involved. The greater reservoir of lubricant available, therefore, the more efficiently can the lubrication problem be handled. The basic solid lubricant-gallium/indium alloy composite itself already contains 20% (wt) filler (GaIn). Incorporation of an additional 20% filler reduces the material available for lubrication purposes by an additional 25%. This reduction in lubricant content to 60% is evidently too low to effectively prevent bearing wear at $900^{\circ}F$ and high load-high speed conditions. An example of this is found in a comparison of Runs #188 and 191. Employing a Cu-W filled retainer, the bearing components from Run #188 suffered the following wear at $900^{\circ}F$ after only 6 minutes of operation:

inner race	-0.094 gms
outer race	-0.143 gms
balls (8)	-0.275 gms cumulative

On the other hand, in Run #191 the same retainer material satisfactorily lubricated a ball bearing operating under the same conditions for 362 hours at room temperature.

Use of a lubricant exhibiting a higher threshold oxidation temperature ($WS_2 \sim 800^{\circ}F$ vs $WSe_2 \sim 650^{\circ}F$) does alleviate this problem.

In Run #189, the same type of bearing system operating under identical load-speed-temperature conditions but using a WS_2/GaIn-Cu-W retainer suffered the following weight changes after 2 hours operation:

inner race	-0.002 gms
outer race	-0.001 gms
balls (8)	-0.029 gms

To summarize the above discussion, experimental evidence indicates (and logic supports) the argument that as operating temperature increases in an air environment, the lubricant in any bearing system is required to handle an increasingly difficult lubrication job. At some point-characteristic of the lubricant in use-the temperature reaches the lubricant's threshold oxidation temperature. If operating temperatures then exceed this level by a substantial margin, the lubricant's effectiveness deteriorates even more rapidly and, in the case of composites - is generally reflected by increased wear of itself due to the greater demands forced upon it. Attempts to impart to the composite greater wear resistance or mechanical strength through the use of metal fillers - *although successful in themselves* - run the risk of further reducing the material's effectiveness as a lubricant. This is reflected not by composite wear but rather by bearing component wear, which in turn precipitates composite wear.

From the results of Run #204, Table VIII, it will be noted that the life of a 204 system operating at 900°F and 10600 rpm was increased to 35 hours during the last reporting period. The bearing carried a load of 50 lb thrust/50 lb radial, and was equipped with a LL shrouded WSe_2/GaIn retainer that had received a post-machining soak of 3 hours at 1030°F.

Runs #207 through #210 were performed on the 207 bearing system at temperatures ranging from 75°F to 900°F. In Run #208 it will be noted that the test program has successfully completed another major milestone by achieving a 105 hour life on a 207 system operating at 600°F and 10,600 rpm. The bearing was equipped with a LL shrouded WSe_2/GaIn retainer and carried a 50 lb thrust/50 lb radial load. Nine titanium carbide balls were used in place of the M-2 tool steel balls with which

the bearing was originally equipped. A second 600°F test on this bearing system (Run #210), operating under a load of 100 lb thrust/150 lb radial, provided a life of 50 hours before cage failure. In both cases bearing performance was quite smooth throughout the test. In Run #209 a 207 bearing, again equipped with the LL, WSe_2/GaIn retainer, operated for a period of 38 hours at 900°F before cage failure due to pocket wear. It is interesting to note that this 900°F performance of the 207 system is slightly better than that of the smaller 204 system.

In the writers' opinion, the successful, long-term operation of the 207 bearing system at both 600 and 900°F has now further extended the state-of-the-art of self-contained, solid lubricated ball bearing systems for high speed-high load applications.

Table IX presents the results of functional tests performed at 900°F on the initial series of composites employing various fillers in low concentrations. Friction-wear screening tests at 900°F had indicated that these composites possessed greater wear resistance than the unfilled WSe_2/GaIn composite. While bearing life in some cases approached that of the WSe_2/GaIn composite, no improvement in life was obtained. In two tests (Runs #218 and #219) an indication of chemical interaction between the filler and the basic composite was observed. Additional work is required in this area before it is determined if any advantage lies in this approach. Again, however, these results emphasize the importance of obtaining functional test data to support bench screening tests.

III. CONCLUSIONS

The following conclusions are drawn from experiments performed during the past quarter:

1. No advantage has been found in substituting metals other than tungsten in copper-tungsten filled composites. The metals investigated were tantalum, molybdenum and silver.

2. Metal filler blends incorporating nickel as one of the filler components suffer severe oxidation at 1000°F.

3. A maximum synthesis temperature of 1380°F (750°C) for WSe_2 appears to be close to optimum with regard to the gallium/indium treatment.

4. The wear resistance of WSe_2/GaIn specimens prepared for evaluation on the Hohman apparatus is not representative of the wear characteristic of a machined retainer unless a coating formed on these specimens during the firing cycle is removed. The depth of penetration of this coating is a function of fabricating pressure (porosity).

5. Bench screening tests indicate that low filler concentrations of 2% to 5% (wt) substantially improve the high temperature wear resistance of the WSe_2/GaIn composite. These fillers include Cu, Ag and CaF_2.

6. The operating life of the 204 system at 10600 rpm in a 900°F-air environment has been increased from approximately 20 hours to 35 hours. The bearing carried a load of 50 lbs thrust/50 lbs radial.

7. Three major milestones have been achieved through the long-term operation of a 207 size bearing at 10,600 rpm and high temperature. These are:

a) 105 hours at 600°F under 50 lbs thrust/50 lbs radial
b) 50 hours at 600°F under 100 lbs thrust/150 lbs radial
c) 38 hours at 900°F under 50 lbs thrust/50 lbs radial

IV. FUTURE WORK

During the next reporting period functional testing will be completed at 900°F on the 204 and 207 size systems. Evaluation of the performance of 206 - Stellite bearings at 1200°F and 204 Kentanium bearings at 1500°F will also be completed.

REFERENCES

1. Boes, D. J. and Bober, E. S., "Solid Film Lubrication Research," Fifth Quarterly Progress Report, March, 1967.

Table I

EFFECT OF METAL FILLERS ON WS_2* /GaIn COMPOSITE STRENGTH

Composition wt %	Compressive Strength
90 WS_2/GaIn** - 5 Cu - 5 Ta	18750
" - " - 5 Mo	18850
" - " - 5 Ag	20400
80 WS_2/GaIn** - 10 Cu - 10 Ta	20800
" - " - 10 Mo	18350
" - " - 10 Ag	19250
90 WS_2/GaIn** - 5 Ni - 5 W	Delaminated during 1000°F cure
" - " - 5 Ta	"
" - " - 5 Mo	"
" - " - 5 Ag	"
80 WS_2/GaIn** - 10 Ni - 10 W	Delaminated during 1000°F cure
" - " - 10 Ta	"
" - " - 10 Mo	"
" - " - 10 Ag	12300
90 WS_2/GaIn** - 6-2/3 Cu - 3-1/3 W	12950
" - 7-1/2 Cu - 2-1/2 W	24550
" - 3-1/3 Cu - 6-2/3 W	16300
" - 2-1/2 Cu - 7-1/2 W	17350

* WS_2 Annealed @ 750°F; Ball-milled 30 minutes.

** 80% WS_2 - 20% GaIn (75% Ga - 25% In).

Note: All pellets pressed at 50,000 psi - Room Temperature.

Table II

EFFECT OF Cu AND Cu-W FILLERS ON SOLID LUBRICANT-GALLIUM/INDIUM COMPOSITES

Composition wt %	Fabricating Pressure - psi	Compressive Strength
90 WS_2/GaIn* - 10 Cu	25000	15300
"	50000	21000
"	75000	21850
"	100000	19800
90 WSe_2/GaIn** - 10 Cu	25000	Pellet delaminated
"	50000	20800
"	100000	15000
90 WS_2/GaIn* - 5 Cu - 5 W	25000	18000
"	50000	18700
"	75000	15800
"	100000	16150
90 WSe_2/GaIn - 5 Cu - 5 W	25000	27950
"	50000	28650
"	75000	17300
"	100000	18700
90 WS_2/GaIn*** - 5 Cu - 5 W	25000	9850
"	50000	12350
"	75000	13600
"	100000	15450

* 80 WS_2 - 20 GaIn (75 Ga - 25 In) wt %

** 80 WSe_2 - 20 GaIn (") "

*** 85 WS_2 - 15 GaIn (") "

Table III

EFFECT OF TEMPERATURE ON FRICTION-WEAR[1] OF VARIOUS COMPOSITES - 3# Line Contact on 1/4" Face

Material Composition wt %	Compressive Strength - psi	75°F μ*	75°F Scar - mm	600°F μ	600°F Scar - mm	900°F μ	900°F Scar
90 WS_2 GaIn - 10 Cu	21000	0.18	3	----	2-1/4	0.11	3[b]
80 " - 20 "	12950	0.17	3	0.22	2	0.34	2-3/4[b]
70 " - 30 "	17050	0.20	2-1/2	0.28	2	0.45	3[b]
90 WSe_2 GaIn - 10 Cu	20800	0.04	2	0.15	3-3/4	0.13	4[b]
80 " - 20 "	27050	0.06	2	0.15	3-3/4	0.42	3-1/4[c]
70 " - 30 "	29030	0.13	2	0.15	4-1/4	0.45	4[c]
90 WS_2 GaIn - 5 Cu - 5 W	18700	0.17	2-1/2	0.14	2-3/4	0.17	2-3/4[a]
90 WSe_2 GaIn - 5 Cu - 5 W	28650	0.10	2	0.04	4	0.20	3-3/4[b]

(1) Hohman test against M2 Tool Steel - 2550 fpm sliding velocity.

* μ = friction coefficient

(a) Good Film

(b) Average Film

(c) Poor Film

TABLE IV

EFFECT OF SYNTHESIS TECHNIQUE AND BALL-MILLING TIME ON 80% WSe_2 - 20% GaIn* (WT) COMPOSITE

Synthesis Temp-°F	Ball-Mill Time-min	Fabricating Pressure-psi	Compressive Strength-psi**
930	15	25,000	15,000
"	"	"	13,750
"	"	100,000	20,250
"	"	"	23,600
930	30	25,000	13,100
"	"	"	10,950
"	"	100,000	20,900
"	"	"	18,450
1380	15	25,000	Delaminated
"	"	"	"
"	"	100,000	18,950
"	"	"	19,350
1380	30	25,000	Delaminated
"	"	"	"
"	"	100,000	21,550
"	"	"	27,900

Synthesis Temp-°F	Ball-Mill Time-min	Fabricating Pressure-psi	Compressive Strength-psi**
930	15	50,000	Delaminated
"	30	"	23,700
"	60	"	15,550
"	90	"	10,450
1380	15	50,000	18,650
"	30	"	14,000
"	60	"	21,400
"	90	"	22,550
930	90	25,000	16,250
"	"	50,000	20,400
"	"	75,000	28,200
"	"	100,000	23,950
1380	90	25,000	22,100
"	"	50,000	23,750
"	"	75,000	24,600
"	"	100,000	23,450

* 75% Ga - 25% In (wt)

** Curing cycle: 15 hours at 450°F; 8 hours at 650°F; 8 hours at 1030°F.

TABLE V

WSe_2/GaIn PERFORMANCE AT 900°F UNDER HIGH SPEED CONDITIONS

2550 fpm - 3 lb Line Contact on 1/4" Face

Test	Material Description: Synthesis-°F	Material Description: Ball-Mill min	Specimen Source	Cure-°F	μ	Scar-mm
1	1380	60	Block*	930	0.15	> 15
2a	930	30	Block	1030	0.17	3-1/2
b	"	"	Opposite side-Block #2	"	0.13	3-1/4
3a	930	15	Block	1030	0.15	3-1/2
b	"	"	Block #3 + 4 hrs-1200°F	1200	0.16	5-1/2
4	1380	15	Block	1030	0.15	4
5	930	60	204 Ring**	1030	0.15	> 15
6	930	60	Same ring as #5	1030 + 4 hrs at 1200	0.15	> 15
7	930	60	Outer surface - ring #5	1030	0.15	> 15
8	1380	90	207 ring**	930	0.17	> 15
9	1380	90	Same ring as #8	930 + 4 hrs at 1030	0.15	> 15
10	930	90	Block	1030	0.15	4
11	930	90	Block	930	0.16	4-1/2
12	1380	90	Block	1030	----	3-1/2
13	1380	90	Block	930	0.17	5-3/4

* 1/2" x 5/8" x 1/4"

** 1.6 O.D. x 0.8" I.D. x 3/4"

*** 2.25" O.D. x 1.625 I.D. x 3/4"

μ Coefficient of Friction

TABLE VI

WSe_2/GaIn PERFORMANCE AT 900°F UNDER HIGH SPEED CONDITIONS

2550 fpm - 3 lb Line Contact on 1/4" Face

Test	Material Description Synthesis-°F	Ball-Mill min	Specimen Source	Cure-°F	μ	Scar-mm
14	930	30	204 ring	43,000-10 min	0.18	> 15
15	1380	15	204 ring	43,000-10 min	0.16	> 15
16	"	"	"	43,000-No hold	0.15	> 15
17	"	"	"	21,000-10 min	0.17	8
18	930	90	Block	14,500-No hold	0.14	3-1/2
19	"	"	"	25,000-No hold	0.15	3-1/2
20	"	"	"	35,000-No hold	0.19	10-1/2
21	"	"	"	48,000-No hold	0.14	> 15
22	"	"	"	60,000-No hold	0.16	> 15
23	930	90	204 ring	11,500-No hold	0.06	> 15
24	"	"	"	15,300-No hold	0.11	15
25	"	"	"	19,000-No hold	0.14	13
26	"	"	"	23,000-No hold	0.20	14
27	#18 test block with face sanded down 1/16"			25,000	0.16	16
28	#12 test block with face sanded down 1/16"			25,000	0.16	16

μ = Coefficient of Friction

TABLE VII

$900^{\circ}F$ WEAR RATE OF VARIOUS COMPOSITES UNDER HIGH SPEED CONDITIONS

2550 fpm - 3 lb Line Contact on 1/4" Face

Material Composition Wt %	Specimen Source	Fabricating Pressure-psi	μ	Scar-mm
80 WS_2 - 20 GaIn	204 ring	43,000 psi-No hold	0.20	4
"	204 ring	21,000 psi-10 min	0.11	4
"	Block	25,000 psi-No hold	0.16	3
90 WSe_2 GaIn-5 Cu-5 W	204 ring	43,000 psi-Hold	0.04	4-1/2
"	Block	25,000 psi-No hold	0.20	3-3/4
90 WSe_2 GaIn-10 Cu	204 ring	43,000 psi-Hold	0.14	3-1/2
"	Block	25,000 psi-No hold	0.13	4
95 WSe_2 GaIn-5 Cu	Block	25,000 psi-No hold	0.05	4
"	Same block with 1/16" face removed		0.03	4

μ = Coefficient of Friction

TABLE VIII—FUNCTIONAL TEST RESULTS - 10,600 RPM

204 BEARING SYSTEM

Run No.	Load-lb Thrust	Load-lb Radial	Temp. °F	Life Hrs.	Ball No.	Cage Type	Cage Fit	Cage Composition - wt %	Failure Mode
188	50	50	900	0.1	8-M2	LL	L10**	$80WSe_2$/GaIn-10Cu-10W	Bearing Wear - Rough Operation
189	50	50	900	2	8-M2	LL	L10	$80WS_2$/GaIn-10Cu-10W	Rough Operating - Stopped for Inspection
190	25	25	900	6	8-M2	LL	L10	$80WS_2$/GaIn-10Cu-10W	Cage Fracture
191	50	50	75	362	8-M2	LL	L10**	$80WSe_2$/GaIn-10Cu-10W	Cage Fracture
192	50	50	900	2.3	8-M2	LL	L10**	$90WS_2$/GaIn-5Cu-5W	One Pocket Bridge Cracked - Rough Operation
193	75	50	900	3.6	7-M2	Insert	L10**	$80WS_2$/20GaIn Ring $90WS_2$/GaIn-5Cu-5W Inserts	Insert Fracture
194	50	50	900	6	7-M2	Insert	L10**	$80WS_2$/20GaIn Ring $80WS_2$/GaIn-10Cu-10W Inserts	Insert Fracture
195	75	50	900	2	7-M2	Insert	L10**	$90WS_2$/GaIn-5Cu-5W	Insert Fracture
196	50	50	900	12	8-M2	LL	L10**	$90WS_2$/GaIn-5Cu-5W	High Wear - Cage Fracture
197(a)	50	50	900	0.7	7-M2	LL	L10**	$85WSe_2$/GaIn-15Ta	Pocket Wear
198(a)	50	50	900	9	7-M2	LL	L10**	$80WS_2$/GaIn-10WSe$_2$/GaIn-5Cu-5W	Cage Fracture - Wear
199(a)	50	50	900	0.7	7-M2	LL	L10**	$90WSe_2$/GaIn-5Cu-5W	Pocket Wear
200(a)	50	50	900	1	7-M2	LL	L10**	$90WSe_2$/GaIn-10Cu	Cage Instability - Pocket Wear
201(a)	50	50	900	5.5	7-M2	LL	L10**	$90WS_2$/GaIn-10Cu	Pocket Wear
202(b)	50	50	900	6.5	8-M2	LL	L10**	$80WS_2$/GaIn-10WSe$_2$/GaIn-5Cu-5W	Cage Fracture
203(b)	50	50	900	8	8-M2	LL	L10**	$90WS_2$/GaIn-10Cu	Cage Fracture
204(b)	50	50	900	35	8-M2	LL	L10**	$80WSe_2$-20GaIn (3 hr soak at 1030°F after machining)	Pocket Wear-Fracture
205(b)	50	50	900	21	8-M2	LL	L10*	$80WSe_2$/20GaIn (24 hr soak at 1030°F after machining)	Pocket Wear-Fracture
206(b)	50	25	900	17	8-M2	LL	L10**	$80WSe_2$/20GaIn (72 hr soak at 1030°F after machining)	Pocket Wear-Fracture
211(b)	50	50	900	27	8-M2	LL	L10*	$80WSe_2$/20GaIn (Commercial WSe_2)	Pocket Wear-Fracture
207 BEARING SYSTEM									
207	50	50	75	20	9-TiC	LL	L10**	$80WSe_2$/GaIn (3 hr soak at 1030°F after machining)	Cage Instability - Very Light Pocket Wear
208	50	50	600	105	9-TiC	LL	L10*	$80WSe_2$/GaIn (3 hr soak at 1030°F after machining)	Wear and Cage Fracture
209	50	50	900	38	9-TiC	LL	L10**	$80WSe_2$/GaIn (3 hr soak at 1030°F after machining)	Wear and Cage Fracture
210	100	150	600	50	9-TiC	LL	L10**	$80WSe_2$/GaIn (3 hr soak at 1030°F after machining)	Wear and Cage Fracture

Bearing components other than cage previously operated for 1100 hours - 75°F - 3400 rpm - 100 lb T/100 lb R

* L10 Fit - 0.020" Clearance between ball and pocket - 0.018" Clearance between cage & inner race

** $85WS_2$/15GaIn

(a) Cage width increased from 0.550" to 0.750"

(b) Cage width = 0.600"

TABLE IX

204* FUNCTIONAL TEST RESULTS

10,600 rpm - 900°F

Run No.	Load-lbs Thrust	Load-lbs Radial	Life hrs.	Cage Composition Wt %	Failure Mode
212	50	50	13	95 WSe_2/GaIn - 5 AgGaIn	Cage Fracture
213	50	50	17	98 WS_2/GaIn - 2 CaF_2	" "
214	50	50	7	97-1/2 WSe_2/GaIn - 2-1/2 Cu	Pocket Wear
215	50	50	7	80% [90 WS_2 - 10 CaF_2] - 20% GaIn	Pocket Wear - Cage Fracture
216	25	50	9	" "	Pocket Wear - Cage Fracture
217	50	50	14	80 WS_2 - 20 GaIn	Cage Fracture
218	50	50	0.2	90 WSe_2/GaIn - 10 CaF_2	Cage Fracture - Material Interaction at 850°F
219	50	50	0.4	" "	Cage Fracture - Material Interaction at 850°F
220	50	50	1.5	47-1/2 WSe_2/GaIn - 47-1/2 WS_2/GaIn - 5 Cu	Chipping and Cage Fracture Bearing Wear

* All retainers equipped with 8-hole LL shroud - M-2 tool steel balls.

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DATE 12-13-66 PAGE 1 OF 1

CUSTOMER WESTINGHOUSE R&D

Q.R. 3856-6 APP'D [illegible] DR. EM

ITI IDENTIFICATION NUMBER 10660 | REV A

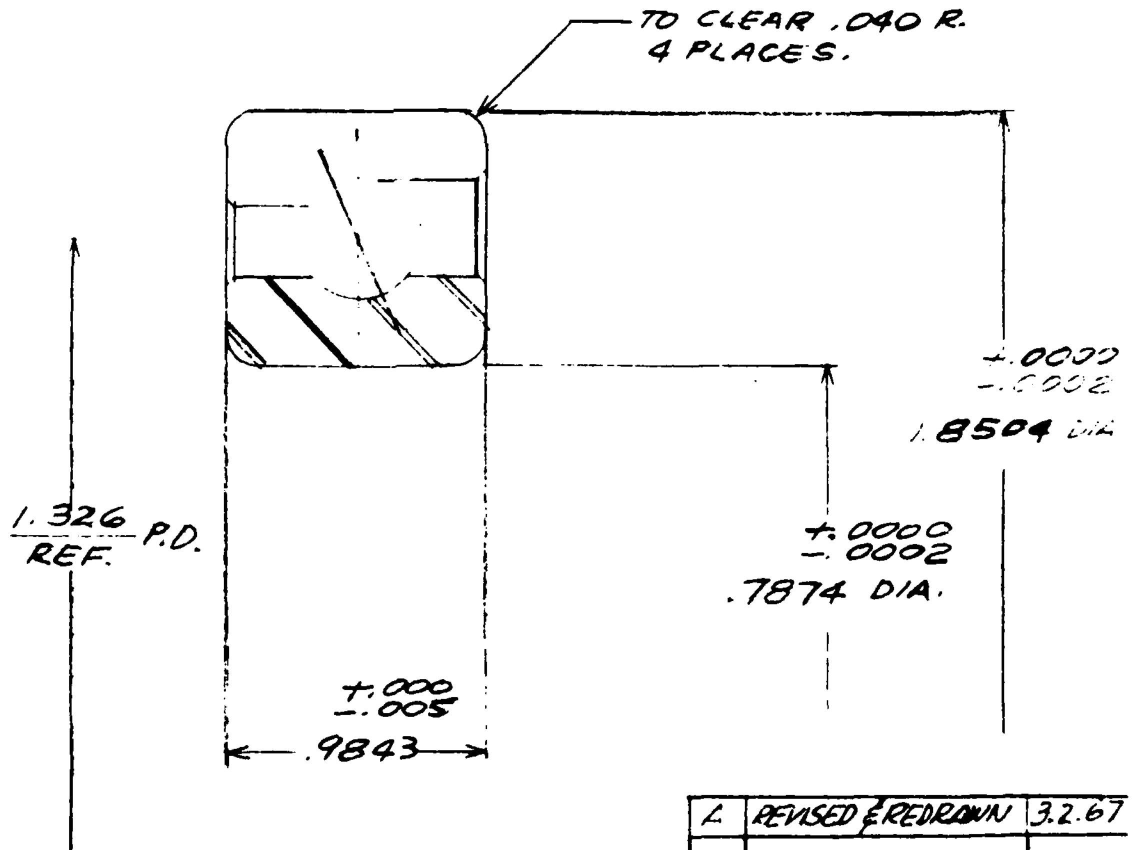
DWG. NO —

RING MATERIAL	ROLLING ELEM. MAT	INTERNAL CLEARANCE	BEARING TYPE (L-117)
K-162 B KENTANIUM	K-162-B KENTANIUM	RADIAL .0055 NOM. AXIAL	ANGULAR CONTACT BALL BRG.

SEP. MAT. AND TYPE	CLOSURE MAT. AND TYPE	CONTACT ANGLE	RACE RADIUS, % BALL DIA.
NONE		[illegible] (NOMINAL)	57 INNER 52 OUTER
		TOLERANCES EXCEPT AS NOTED: ABEC-5	NO. AND SIZE ROLL. ELEMENTS: 10-9/32 DIA. GR. 10 BALLS

OUTER RING	INNER RING	LUBRICATION/PRESERVATIVE
OD 1.8504	OD 1.129	
ID 1.523	ID .7874	SEPARATOR
WIDTH .9843	WIDTH .9843	O.D. I.D. WIDTH

NOTES: 1. RACEWAYS DEPTH: 15% OF BALL DIA.



LTR	DESCRIPTION	DATE
A	REVISED & REDRAWN	3.2.67

REVISIONS

Figure 1. High Temperature Bearing Design - Outer Race Relieved

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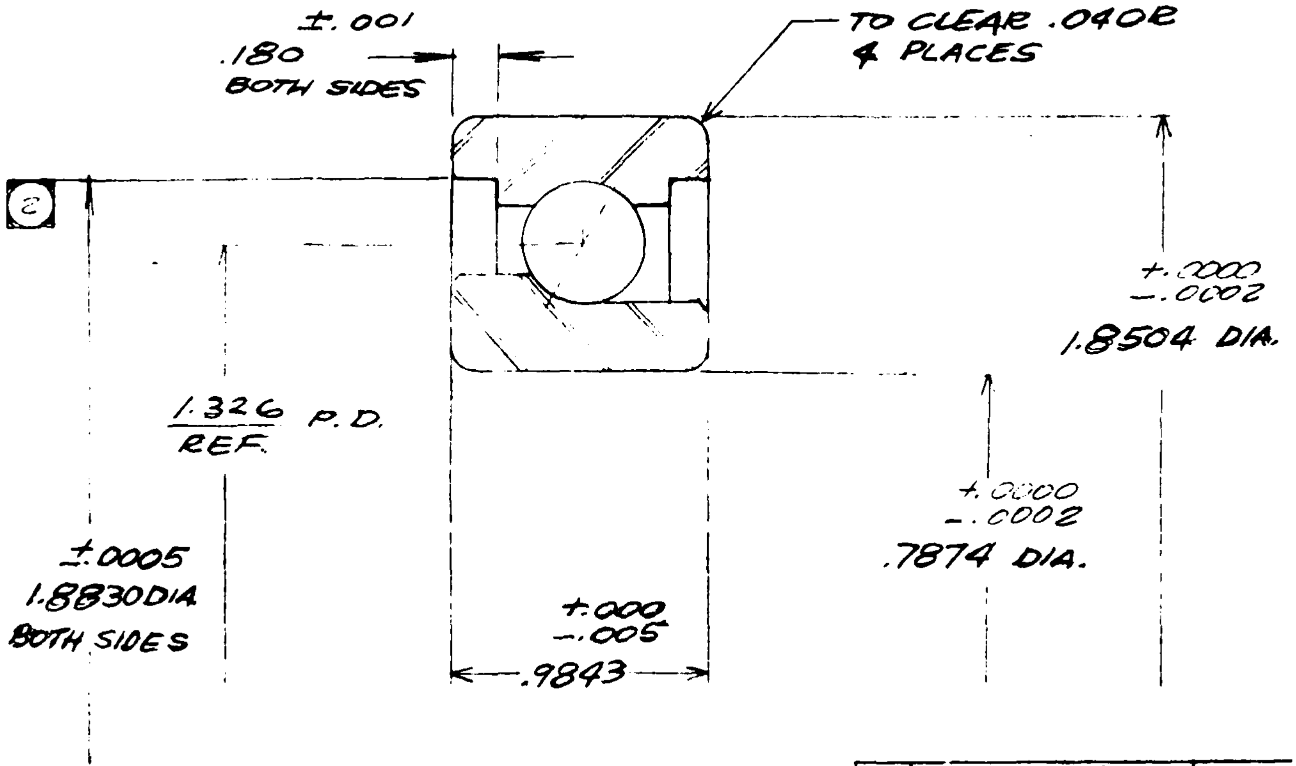
Q.R. 5037-7 APP'D [illegible] DR. [illegible]	ITI IDENTIFICATION NUMBER 10810 — REV. A	CUST. REF. WESTINGHOUSE R&D — DWG. NO. ———

RING MATERIAL: K-162-B KENTANIUM	ROLLING ELEM. MAT.: K-162-B KENTANIUM	INTERNAL CLEARANCE: RADIAL .0055 NOM. AXIAL ———	BEARING TYPE (L-117): ANGULAR CONTACT BALL BRG.
SEP. MAT. AND TYPE: NONE	CLOSURE MAT. AND TYPE:	CONTACT ANGLE: 15° (NOMINAL)	RACE RADIUS, % BALL DIA.: 57 INNER 52 OUTER
		TOLERANCES EXCEPT AS NOTED: ABEC 5	NO. AND SIZE ROLL. ELEMENTS: 10. 9/32 DIA. GR.10 BALLS
OUTER RING: OD 1.8504, ID 1.523, WIDTH .9843	INNER RING: OD 1.129, ID .7874, WIDTH .9843	LUBRICATION/PRESERVATIVE:	
		SEPARATOR: O.D. I.D. WIDTH	

NOTES: 1. RACEWAYSDEPTH : 15% OF BALL DIA.

2 DIA. CONCENTRIC WITH O.D. WITHIN .002 TIR.



LTR.	DESCRIPTION	DATE
A	ADDED LUBRICANT RECESSES	3.16.67

REVISIONS

Figure 2. High Temperature Bearing Design - Inner Race Relieved

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13. ABSTRACT

This report describes progress during the seventh quarterly period in a program designed to develop a solid film lubricated ball bearing system capable of operation under high speed, high temperature oxidizing conditions. The program's ultimate goal is long-term ball bearing operation at 1500°F and speeds of 10,000 to 30,000 rpm under atmospheric conditions simulating sea-level to 200,000 ft altitudes. A second program objective is to provide parametric design data relating the operating life, load, bearing size, speed, temperature and environment of these bearing systems.

In the materials development area, this report describes further efforts towards improving the high temperature friction-wear characteristics of unique self-lubricating composites employing WSe_2 or WS_2 in combination with a gallium alloy.

In the area of functional testing, the results of thirty-three tests on 204 and 207 ball bearings that were evaluated during this reporting period are described. The bearings were operated at temperatures up to 900°F and speeds of 10,600. Two significant results obtained during this reporting period are the operation of (1) a 207 ball bearing in 600°F-air at 10,600 rpm for a period of 105 hours, and (2) an identical bearing system at 10,600 rpm in a 900°F environment for a period of 38 hours. In both cases the bearing carried a 50 lb thrust/50 lb radial load.

DD FORM 1 JAN 64 1473

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RM 35054

14 KEY WORDS	LINK A		LINK B		LINK C	
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Gallium						
Indium						
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